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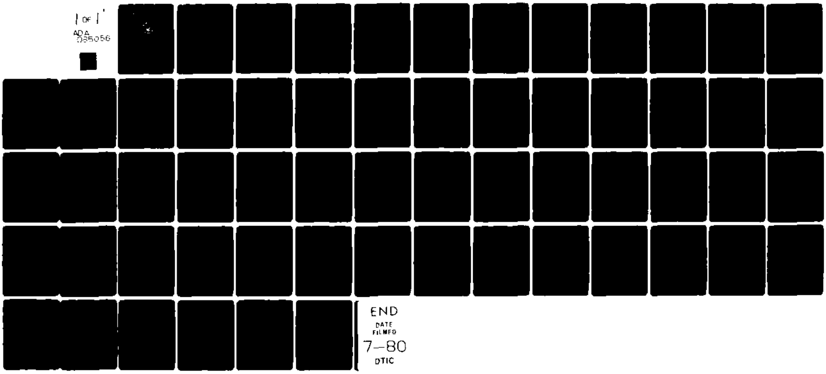

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THESIS

MICROSTRUCTURE PROFILES

by

Carl Christiansen

March 1980

Thesis Advisor: E. Thornton

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#20 - ABSTRACT - Continued

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Spectra of both the gradients of the temperature as well as the perturbations on the mean profile were calculated. It was determined that the microstructure spectrum indicates an increase in density at frequencies greater than 1 cycle per meter. Cox numbers were calculated but are considered to be of marginal value since these data cover a portion of the ocean that consists of sharp gradients.

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Microstructure Profiles

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Submitted in partial fulfillment of the
requirements for the degree of

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I. INTRODUCTION

The term microstructure has had a relatively recent introduction to Oceanography. Its original usage referred to almost any events or phenomena that were of an order less than those of the gross structure. There was no terminology in usage for mesoscale phenomena. The exact meaning of the term microstructure changed rapidly and had never been fully agreed upon, but the general trend was to use it for smaller and smaller scales. The term fine structure has recently been introduced to fill the broadening gap between gross structure and microstructure. There is general agreement now that fine structure refers to events on the order of meters and the term microstructure, in its present usage, has come to indicate fluctuations in the centimeter range. The use of platinum thin film probes has shown that the gradient spectrum can extend to wavelengths as short as 1 centimeter. The existence of microstructure less than 1 centimeter would necessarily have to be a short lived phenomenon (less than 3 minutes) due to the molecular diffusion of temperature. Consequently 1 centimeter is often called the diffusive cutoff and events of a lesser scale are not considered of great significance.

A study of temperature microstructure in the mixed layer and thermocline (or pycnocline) has been undertaken as a component of an overall effort to investigate temporal and spatial fluctuations of sound velocity in the ocean. It is the density microstructure as determined by both temperature and salinity that directly determines the acoustical indices of refraction; however, in the mixed layer and thermocline, the temperature excursions from the mean overwhelmingly dominate the salinity excursions. Past field investigations of microstructure [Ref. 4] have consistently shown that vertical salinity and temperature fluctuations on the microscale compare favorably with those of the gross features as depicted on a T-S diagram to produce general stability, even in events of temperature inversions. Salinity excursions generally have much less of an effect on density distribution than the temperature in the upper ocean layers and their behavior can generally be anticipated from the temperature profile. Consequently, a proper understanding of the temperature microstructure in the upper layers should yield some significant insight into the behavior of the coefficient of variation of sound [Ref. 23].

The principal objective of this thesis is to produce a good description of the temperature microstructure in a single column of water as it changes during a period of several hours. Although exact dynamical or kinematic mechanisms will not be offered, a good description should help provide some valuable information to the theoreticians. It was originally intended to observe the effects of insolation on the mixed layer and thermocline. Ship availability constraints however did not permit a wide range of dates for data collection and unfortunately the day selected for making the measurements was continuously foggy and so did not provide the desired direct insolation.

Fortunately, however the site selected did prove to be of interest by providing a stable temperature inversion which remained in evidence throughout the day.

Repeated vertical temperature profiles in a single column of water are required in order to observe, at least to some degree, the history of evolution of the mixed layer, thermocline and sub thermocline microstructure. Because of the numerous large scale and microscale velocity and directional shears throughout a column of water, completely vertical profiles could not be sampled directly. What was observed were vertical temperature profiles taken by a free falling instrument package subject to the accumulated velocity shears of the water column. The instrument package (or profiler) was essentially free drifting. As a result, the assumption can validly be made that advection plays a negligible part in the changing characteristics of the observed microstructure. Measurements of the driving forces which include atmospheric temperature, pressure and humidity, water surface characteristics, and wind stress were also taken [Ref. 6].

II. BACKGROUND

The approach toward the temperature measurements in this experiment was one that sought to mechanically isolate temporal microstructure variations from spatial. Isolation was accomplished by reducing advective effects as much as possible during the length of the experiment by drifting with the current which decoupled the sensor from surface phenomena. As well as can be determined by a thorough scan of current literature, the data appear to be unique in their application to the study of temperature microstructure. Past investigations sought microstructure data for reasons other than observing its relationship to driving mechanisms. The effects of advection and horizontal separation of profiles were not considered significant. In Gargett's [Ref. 5] paper for example, her vertical profiles were not truly vertical but were produced by towing an instrument package through the water at angles to the horizontal of less than 17 degrees. She then assumed the profiles to be vertical if not throughout, at least in local sections. The instrument was decoupled from the ship movements by a servo-winch.

Gallagher [Ref. 3] gets vertical profiles from a free falling instrument loosely tethered to a surface buoy and consequently he does get realtively true vertical profiles. His instrument however is ultimately connected to the research vessel and so is not free drifting. He takes four profiles along a line normal to the coast of Oahu with horizontal separation on the order of miles.

Gregg [9] made some hypotheses from vertical profiles taken during the Fresnel cruise (1971) in which several profiles were taken in unrelated positions off Cabo San Lucas, the southern tip of Baja California. Here there is strong interaction between the California current and the Equatorial Water Mass. This ensemble of data represents individual, that is unrelated spatially or temporally, profiles through distinctly heterogeneous water columns. Gregg's data taken from the Tasaday cruise [5] of the research vessel Thomas Washington (1974) was by his own description "ad hoc." Although the profiles individually appeared to have application to the subject of this thesis, they represented only very anomalous conditions of mechanical mixing due to a storm passage. Furthermore, insolation was greatly reduced during this inclement period. Any continuity that may have existed, was further degraded due to great spatial variability through three distinct water masses.

The conjunctive work of Gregg and Cox [7] was based on a single vertical profile in an area of suspected strong internal wave and tidal motion. The same was true of the joint work of Cox and Osborn [16].

The one investigation to have involved a study of diurnal variations in temperature microstructure with a concurrent investigation of the effects of the microstructure on acoustic propagation was made by Rickard, _et al._, in 1977 [17]. He performed his experiment, however, in coastal waters with a moored array; this did not provide vertical profiles but rather a time series of indistinguishable temporal and advective contributions. Two temperature sensors were placed in an area of very shallow water, 21 meters, which was greatly influenced by variable tidal currents. The shallowness did not provide for a thermocline, the most dynamic region of a microstructure profile.

Microstructure investigations have all shown that large scale temperature features can be resolved into several stable layers separated by sharp interfaces, or sheets, a meter to a few centimeters thick. In a subjective treatment of this phenomenon, Woods [24] was the first to use the descriptive terms of layers and sheets. Significant temperature changes are concentrated into regions generally smaller than a meter thick where the measured gradients are often more than ten times the average gradient. The horizontal extent of the fine structure regions of high gradient has been generally observed to be greater than 750 meters in the seasonal thermocline [16]. That is, finescale features are statistically and subjectively consistent over large horizontal distances. Horizontal coherence is diminished with smaller scale features, less than 1 meter, and with depth below the seasonal thermocline.

Mintzer was the first to predict that the temperature microstructure in the sea was the cause of acoustic intensity fluctuations. Sagar [19] further proposed that a definite correlation probably existed between the microstructure and solar radiation. Investigation proved Sagar's proposal to be correct. No clearly defined relationship was found however to exist between the behavior of the temperature microstructure and any other environmental parameters. That a relationship should exist seems reasonably obvious and there is much investigation currently underway that could tie the microstructure to the processes of forced convection as well as free convection.

The thickness of the surface mixed layer is influenced by two surface induced processes, mechanical mixing, or forced convection, and convective mixing or free convection. Mechanical mixing includes all of the vertical turbulent mixing processes resulting from the transfer of momentum from the wind. Convective mixing occurs as a result of instability generated at the surface by cooling and evaporation of fresh water.

The surface forcing functions provide the buoyant and mechanical energy for mixing and stirring respectively. However, it is the turbulent microscale processes that distribute the energy which leads to the production of the mean temperature pattern. Unfortunately, turbulence in the microscale is elusive and short-lived and consequently difficult to investigate.

Insight is provided from the examination of the profiles of small scale density fluctuations such as those of Gregg and Cox [7]. Current research endeavors continue to include more and better profile data collection and attempts to relate these data to causal events. A variety of approaches have been tried, as can be seen in the section dealing with theory. Encouragement for fully resolving the oceanic temperature microstructure comes from the model of Osborn and Cox [16] which relates the vertical diffusion of heat to the variance of the temperature gradient (see Theory).

There seems to be a growing consensus that fine structure variations determine the scale for the microstructure in that different fine structure regimes provide settings in which particular levels of microstructure activity are likely. Specifically, it would be advantageous to determine what length scales make major contributions to the variance of the microstructure gradients $(\nabla T)^2$, how the larger scales (fine structure) influence the microstructure, and how the microstructure varies in time and space.

The other important feature in the upper ocean, the antithesis of microstructure, is turbulence. To fully understand the activity in the water column, it is necessary to note where turbulence occurs. It is important to ascertain how often it is present, at what depths, what scales are present and most importantly the relationship between turbulence and the temperature microstructure.

III. THEORY

The upper layer of the ocean which includes the mixed layer and is bounded below by the seasonal thermocline is usually regarded as that part of the water column with the strongest vertical mixing. Mixing is a result of generated forced and free convection. Layering is to be expected, and has long been noted, in and below the very stable region of the thermocline. When microstructure and even fine structure profiles were first collected, it was somewhat unexpected and enigmatic to find that a microstructure sometimes existed even in the mixed layer. Microstructure presence in the mixed layer is an indication of weakness of turbulence in this region. Here the weak turbulence is not capable of breaking up the inhomogeneities introduced. That is, the turbulence is not capable of mixing the entire layer.

Large scale thermal structure is undoubtedly initiated by the interleaving of various tongues of water, usually in the area of water mass convergence or at fronts. The thrust of a great deal of current research is toward the understanding of the processes that contribute to the refinements of these large scale interleavings into fine structure and ultimately microstructure. In order to discover the causal agents that develop this stratification, direct evidence is needed about the vertical mixing rates and the processes involved.

Consider the vertical transport of momentum through the laminae. In the weakly stable mixed layer, momentum is primarily transported by turbulent diffusion processes. In a stratified fluid, partial mixing usually results in the formation of additional layers. Even though these layers may indicate temperature inversions, stability is almost always preserved by a compensating salt structure. In the sheets, whatever turbulence exists is suppressed by the stable density gradient. In the case of the thermocline, the turbulence is greatly diminished at the centers of well established sheets. All vertical transport through the sheets must then be due to molecular diffusion which is one or two orders of magnitude less efficient than turbulent diffusion. Thus, the vertical fluxes of heat, salt and momentum in the turbulent mixed layer are essentially decoupled from those of the underlying stable water column because the mixing energy comes from above [Ref. 9].

A diurnal thermocline can be created by progressive warming, or freshening, of the top 10-30 meters. The increased stability causes stratification which will damp wind driven turbulence and if sufficiently large, will establish the base of a new, shallower mixed layer. Decay of this stable region into several laminae has been observed to take place in the absence of surface forcing. Breakup of the discontinuity zone from below also occurs as mixing weakens which leads to a progressive blurring of the diurnal thermocline. Such modification is accomplished either by diffusion or internal gravity wave forces. It is at the site of these discontinuities (thermocline) that pronounced steps are often introduced.

The layers produced can have quite long lifetimes, at least on the order of tens of minutes, and even up to hours. The turbulence is usually weak and incapable of breaking up the stratification. The turbulence seems to develop only within the layers and is characterized by small Reynolds numbers [Ref. 15]. The stability that exists in these layers tends to suppress turbulence and favor the development of strong internal wave activity. Thus, the ability to be able to distinguish between a random ensemble of internal gravity waves (indicating layering) and turbulence would be very desirable.

Convection (turbulence) can be set up by the process of differential diffusions and by Kelvin-Helmholtz shear instabilities, the latter being a result of the internal wave phenomena. "Thus, the layered structure is at once both the result of and an encouragement to vertical mixing" [Ref. 3]. It is evident now, that when dealing with temperature microstructure, the combined effects of advection, lateral convection, internal waves, molecular diffusion, momentum flux and double diffusion are all important processes. To describe their combined product is the first step toward distinguishing individual contributions.

A. COX NUMBERS

An often used tool in describing the microstructure with temperature data alone is the Cox number [Ref. 16], which is shown in equation one below. Cox numbers represent the normalized variance of the temperature gradients and are taken to be a measure of the intensity of small scale turbulent mixing. A rough depth dependence has been suggested for the Cox numbers [7], but this is for deep ocean profiles well below the depth of themain thermocline. The fact that the Cox number represents a normalized quantity makes it a better basis for comparison of microstructure activity since the mean gradients differ appreciably. The Cox number is given in terms of the temperature, T', by

$$C = \frac{\overline{\left(\frac{\partial T}{\partial z}\right)^2} - \left(\frac{\partial \overline{T}}{\partial z}\right)^2}{\left(\frac{\partial \overline{T}}{\partial z}\right)^2} = \frac{\overline{\left(\frac{\partial T'}{\partial z}\right)^2}}{\frac{\partial \overline{T}}{\partial z}} \qquad (1)$$

where overbars indicate time averaging, the primes indicate turbulent temperatures and $T' = T - \overline{T}$.

Comparisons between Cox numbers averaged over entire records often show marked differences. The records can then be decomposed into short vertical segments in an attempt to relate the dissipation rates to the larger scale features of the records. Osborn and Cox [16] derive an expression which relates the vertical diffusion of heat to the variance of the temperature gradient. This balance between the production of local temperature fluctuations by vertical turbulent motion and dissipation of the fluctuations by molecular diffusion can be written

$$\overline{\omega' T'} \frac{\partial \overline{T}}{\partial Z} \simeq -\kappa \overline{\left(\frac{\partial T'}{\partial z}\right)^2} \tag{2}$$

where κ is the coefficient of thermal diffusivity.

If the vertical heat flux is parameterized by an eddy diffusivity coefficient [5], then:

$$\overline{\omega' T'} = - K_z \frac{\partial \overline{T}}{\partial z} .$$

Substituting equation (2),

$$K_z \left(\frac{\partial \overline{T}}{\partial z}\right)^2 = \kappa \overline{\left(\frac{\partial T'}{\partial z}\right)^2}$$

or,

$$K_z = \text{Const.} \frac{\kappa \overline{\left(\frac{\partial T'}{\partial z}\right)^2}}{\left(\frac{\partial \overline{T}}{\partial z}\right)^2} \tag{3}$$

The constant of proportionality of equation (3) varies between 1 (complete isotropy) and 3 (complete anisotrophy). Therefore the Cox number is proportional to the ratio of turbulence to the thermal diffusion rate.

$$C \propto \frac{K_z}{\kappa} \tag{4}$$

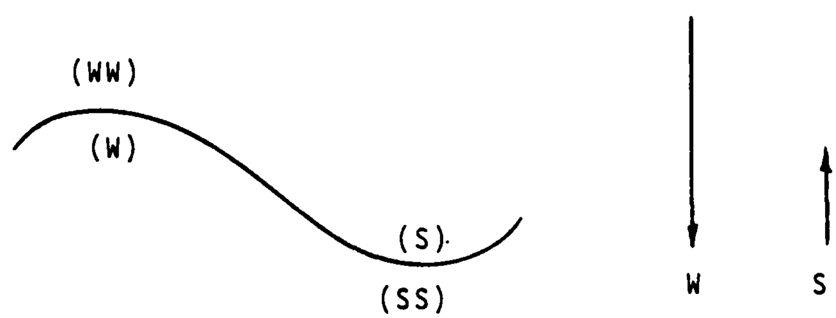
B. DOUBLE DIFFUSION

Double diffusion is now known to be a ubiquitous phenomena in the ocean. The difference in molecular diffusivities of heat and salt in water have a significant effect on the production of relatively well mixed layers and the transport of heat and salt between them. Because the diffusion rate of heat is about 100 times faster than that of salt, some interesting phenomena can take place at sites of large density gradients. At sheets, or interfaces, the molecular processes are of great import.

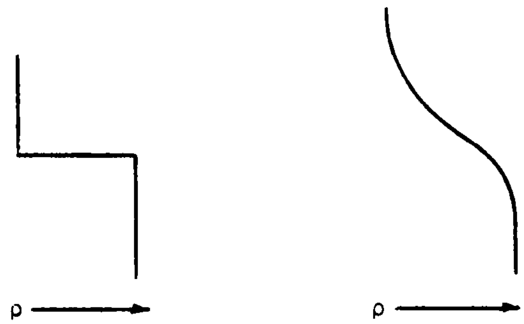
Some interesting laboratory experiments were done by Turner [22] with salt and sugar diffusion processes. Specifically studied was the behavior of intrusions in an existing density gradient having different T-S properties from the intruding fluid.

In a two layered system having a single density interface, three possibilities exist.

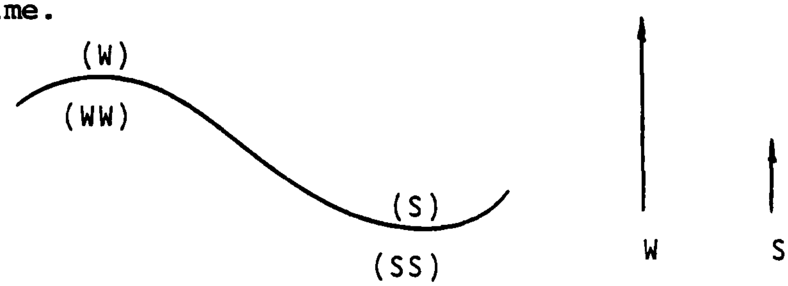
(1) Warm fresh water over cooler saltier water provides the setting for modification of thealready strongly stable structure to a less stable stratification. Consider the graphic approach below where (ww) is relatively warm, (w) is relatively cool, (ss) is relatively salty and (s) is relatively fresh.



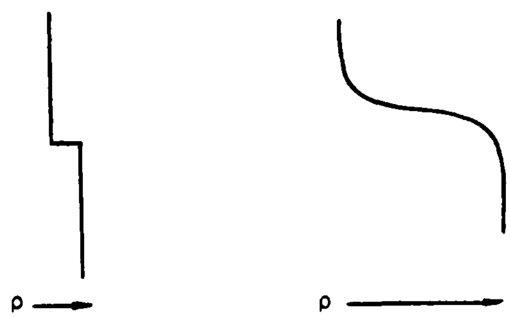
In this case both heat and salt work together to destroy the sharp interface and produce a stable, continuous density profile.



(2) Cool fresh water over warm salty water provides a moderately stratified setting which will increase its stability with time.

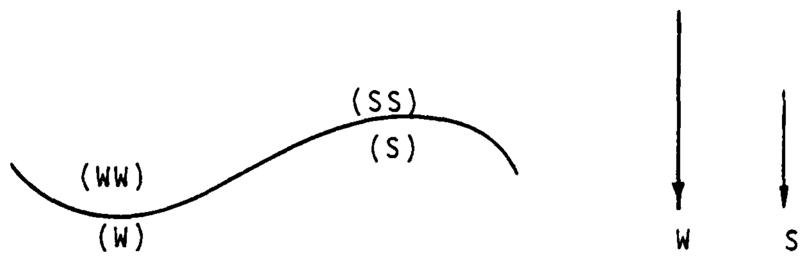


In this case the rapid diffusion of heat produces a more isothermal layer thus accentuating the salt discontinuity and thereby the stratification.



This process also produces convective stirring within each layer. As the water immediately above the interface is warmed, it becomes lighter than the surrounding water and is consequently buoyed. Likewise the water immediately below the boundary is cooled, becomes heavier than the rest of the layer and sinks.

(3) The third and perhaps most interesting case is the inherently unstable case of warm salty water over cooler fresher water.



Here the rapid diffusion of heat downward leaves an uncompensated salt inversion which creates an unstable situation. Any irregularities at the interface tend to become more prominent and this leads to what is knwon as salt fingering. The rate of diffusion of temperature and salinity along the microstructure gradients sets a limit to the smallest significant scales of fluctuation. This diffusion cutoff, as it is called, seems to be at about 1 centimeter [Ref. 3, figure 10].

Since the diffusion rates are known (for sea water κ = 0.0014 cm/sec.), it is possible to calculate an effective "time since formation" of these regions of high gradient (sheets). If it is assumed that there is a step change in temperature, ΔT, created at time T = 0, then the interface thickens and the gradient weakens with time according to the formula below.

$$\frac{\partial T}{\partial z} = \frac{\Delta T}{(4\kappa e^{t})^{1/2}} \qquad (5)$$

The half thickness $z = 4\kappa t$ within which the gradient has decreased to $1/\theta$ of its peak value can be used to estimate the time since formation.

C. KELVIN-HLEMHOLTZ INSTABILITY

The lamination of the sheets and layers is actually a layering of thick regions of moderate stability with interleaving sheets of high stability. In the weakly stable layers, the fluid is turbulent and momentum is transported by eddy diffusivity. In the sheets however, the turbulence is suppressed by the strong stability. In the sheets of the thermocline, the turbulence is suppressed almost entirely. All vertical transport through these sheets is a result of molecular action. Since molecular viscosity is two or three orders of magnitude less than eddy viscosity, these sheets represent shear discontinuities (slippery surfaces) where adjacent layers can actually flow in different directions with different velocities.

A density profile would be most appropriate for observing shear instabilities, however with a gross S-T-D trace, certain assumptions can be made about the salinity gradient on the microscale [Ref. 16]. These salinity assumptions permit speculation about the time scale of the laminal interfaces, that is the Brunt-Vaisala frequency, which is the natural frequency of oscillation of a fluid when it is displaced vertically by a small amount. The Brunt-Vaisala frequency refers to the natural mode of the internal waves that travel along the interface much as surface waves travel along the air sea discontinuity. Internal waves are specifically a manifestation of the sheet discontinuities. The greater the magnitude of the discontinuity the higher is the Brunt-Vaisala frequency. The frequency of oscillation, N, is given by

$$N^2 = -\frac{g}{\rho}\frac{\partial \rho}{\partial z} \tag{6}$$

It is reasonable to assume that microscale salinity fluctuations are proportional to temperature fluctuation in the same way that they are related in a gross T-S diagram; the Brunt-Vaisala frequency then is given approximately as:

$$N^2 = -\frac{g}{T}\frac{\partial T}{\partial z} \tag{7}$$

However, such an assumption is inappropriate in regions of stable temperature inversions because the inferred density structure would be unstable. Using temperature data alone, Cox [16] found that "the minimum period of internal wave activity was comparable to estimates of time since formation." Woods [25] found that the mean Brunt-Vaisala frequency in the summer thermocline off Malta was about 12 cycles per hour, but there were several temperature sheets where the frequency rose to 1 cycle per minute. Those sheets are sites for the generation of turbulence caused by the Kelvin-Helmholtz phenomena.

As stated earlier in this section, a property of the lamination is that it is both a result and an encouragement to the formation of internal gravity waves. Upper limits for the periods of internal waves are set by the thickness of the layers above and below the sheets. If the average thickness of the bounding layers is H, then $2\pi H$ is the longest sustainable wavelength that can propagate along the discontinuity [Ref. 25]. Similarly, if the sheet thickness is h, then $2\pi h$ is the shortest wavelength. Internal waves can become unstable as a result of the transfer of energy of the perturbations (eddies) to mean motion. The instability is eventually relieved by the breaking of the wave and the ultimate release of the mean kinetic energy to turbulence. The Kelvin-Helmholtz instability is the result and its product is the generation of turbulent patches on the sheets. Thorpe [21] found Kelvin-Helmholtz instability mechanisms in the Loch Ness as the major cause of turbulence below the well mixed layer. After the internal waves have broken, smaller secondary breakers develop with a cascading to smaller scale turbulence, eventually the entire sheet becomes turbulent and floats like a raft on the adjacent layers. The patch of turbulence thickens by entraining fluid from adjacent layers until the overall shear is decreased to where the instability can no longer exist; this happens when the region of turbulence approaches four times the original sheet thickness. As the turbulence subsides, two new sheets can form on the boundaries of the turbulent region [Ref. 15]. Repetition of this process creates more and more microstructure, or sharpens existing structure. Figure 1 gives a simplistic depiction of the growth and decay of a Kelvin-Helmholtz event.

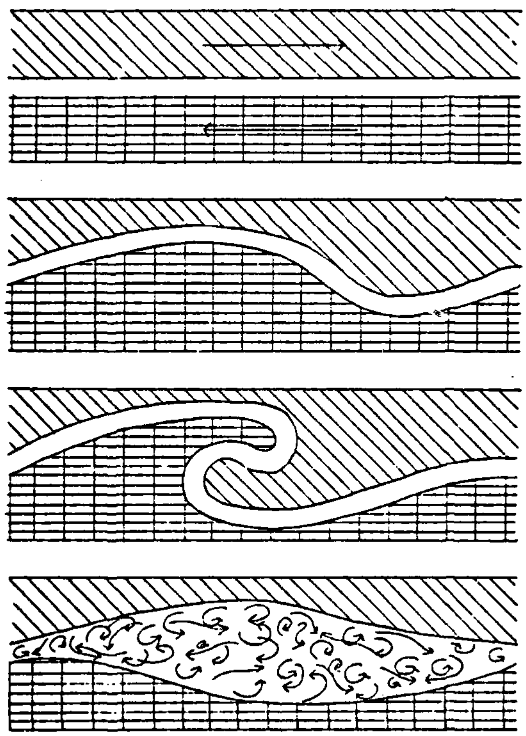


Figure 1. Kelvin-Helmholtz Event

IV. EXPERIMENT

A. OBJECTIVE

The objective of the experiment was to observe the thermal microstructure of the water column in relation to solar heating by obtaining sequential vertical profiles of temperature through a single column of water. Numerous past experiments have been conducted to sense microstructure in a vertical profile but all, so far, have been complicated by either advection or spacial separation of the profiles. Interpretations therefore have been speculative regarding temporal variations. The experiment was designed to allow the profiler to drift with the velocity of a single integrated water column. Advection or spatial variation is not eliminated, but is minimized to acceptable levels.

B. EQUIPMENT

1. Profiler

The profiler was simply an aluminum frame which held the sensing equipment, underwater connections and buoyancy compensating weights and floats. At the very bottom of the profiler was a 1 meter horizontal bar that held up to six thermistors in a horizontal configuration as shown in Figure 2. The profiler has slight negative buoyancy and so was free falling but had to be manually surfaced since the solenoids on the flotation chamber were inoperative.

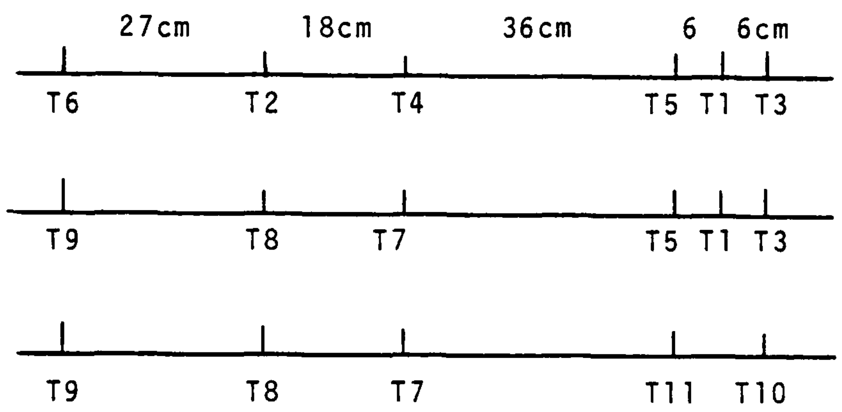


Figure 2. One Meter Thermister Array for Three Dates with Corresponding Thermistor Numbers

2. Thermistors

Simplicity of operation, relatively low cost and large signal make thermistors easier to use than platinum thin film sensors. The thermistors used in the experiment were Veco (42A70) hermetically sealed, bead in glass probes. The thermistors consist of a metallic oxide semiconductor bead, embedded in solid glass with a 7-9 mil internal diameter. Fabula [1] has shown that the differences in thermal properties of water and glass are negligible but that response depends on both size and shape as well as speed at which the probe travels through the water. Lueck, Hertzman and Osborn [14] did a very diffinitive laboratory experiment investigating the spectral response of thermistors. They did experiments on several types of bead, rod and plate thermistors. The rod thermister used had almost identical sepecifications to the one used in this experiment. In fact, what slight differences there were, were in favor of the Veco thermistor. In particular the Veco thermister had a smaller outside diameter giving it a more rapid response time. Consequently the results of Lueck's experiment can be comfortably applied to the thermistors used.

The fastest rate of descent of the probe was 44 cm/sec. In most cases, the rate of descent was appreciably less. It can be assumed then that since even the worst case in Lueck's experiment gives a resolution of 6.7 cm or better, that the sample rate of 6.6 cm used for this profiler is resolvable.

3. Pressure Transducer

The pressure transducer used was made by Teledyne Tabe (2101) and had a full scale output from 0-200 psi. Local resolution is considered infinite while absolute resolution because of hystersis and repeatability is about 5 cm.

4. Controller

Sampling of the thermistors was controlled by a Hewlett Packard 9831A computer. The pressure transducer signal was continuously sampled and at depth intervals of 6.6 cm a temperature sample from each thermistor was recorded by the HP9831A. Hence the sampling wat not rate of fall dependent, but determined by the measured depth.

C. PROCEDURE

All data was collected on October 11, 1978 outside of Monterey Bay at 36-42.13N and 122-1.76W. During this period, the R/V ACANIA was able to maintain position within approximately 500 meters. The profiler was loosely tethered to the Acania for purposes of equipment recovery as well as data telemetry. The tether was composed of a neutrally buoyant shielded rubber cable for data transmission and a second tether of 3/8" nylon line for the purpose of instrument recovery. This method was sufficient to decouple the instruments from ship movement.

As the probe was raised to the surface, it was again coupled to the ship and remained so until a new profile was begun. Three or four profiles were taken during each recording period, the periods being approximately 1 hour apart.

Although it was not the intent of this experiment to show causal events to the temperature microstructure, atmospheric forcing data was collected for future use in calculating heat fluxes and wind stresses. Since the focus of this experiment was on microscale processes in the mixed layer and thermocline, the two most disappointing forcing phenomena were the large, long period swell coming from sustained storm activity to the northwest and the lack of direct insolation during the experiment.

Unfortunately it was foggy fully 90% of the time on station. This of course thwarted the main thrust of the experiment--to observe microstructure changes during the course of a full day of insolution. Whatever slight insolution there may have been, was rapidly and deeply mixed by the strong surface wind stress.

Another major disappointment was the inability to get any salinity profiles. Although two S-T-D probes were aboard, neither one was in working condition except for the temperature sensor component, which was not needed. The gross temperature features were confirmed by frequent XBT drops.

V. RESULTS

A. METEROLOGICAL DATA

The first thing that must be realized when reviewing the accumulated data is that is is representative only of very anomalous conditions. In particular, the forcing functions did not cooperate in a manner that permitted detection of near surface microstructure phenomena. However, a very interesting temperature inversion containing microstructure was present.

The first and most pervasive disappointment was the almost complete absence of direct insolation. The R/V ACANIA took station at approximately 0630 or thirty minutes before sunrise. As dawn approached, a light patchy fog began to form. Eventually the light fog coalesced enough to completely obscure the sun from view. During the entire morning, the sun was never seen directly. The sun did eventually break through the fog at 1430 as the experiment was terminating. The insolation quantitatively measured using a pyrometer is given in Table 1.

Another major disappointment was the very strong wave and swell activity. The former is an indication of the wind stress applied to the sea surface, which was considerable. The swell constituted a record of the accumulated wind stresses over the previous several days. A sustained, and very deep low, centered in the Gulf of Alaska for the previous two weeks created continuous trains of long period, high amplitude swell. The combination of the applied surface stressed and the higher order effects of the long period swell contributed greatly to the maintenance of the isotropic mixed layer.

B. PROFILES

Each profile sampled the water column with a minimum of three thermistors and a maximum of five. This was done in order to provide a measure of horizontal separation and to provide duplicity, which since not all thermistors were reliable, proved valuable. Excepting run number one, only those thermistors that were fully responsive and reasonably noise free, were plotted and subsequently analyzed. Profile number one (Figure 3) is used to exhibit all cases of thermistor response. Thermistor i (T1) can be seen as an example of a noisy thermistor while T2 is an example of a poorly responsive thermistor. Both T3 and T5 appear to be responding correctly. This is confirmed by subsequent profiles where T3 and T5 continue to provide good response while T1 gets noisier.

It is interesting to note on the sequence of profiles (Figures 3-8) the presence of a prominent and also very anomalous temperature inversion as seen in perspective on the XBT profile (Figure 9) and in detail on the microstructure profiles. This inversion is generally centered between -20 and -33 meters. There seems to be a general deepening of the center of the inversion accompanied by shorter period vertical translations of the structure, probably due to the presence of internal wave activity. As well as can be determined, this inversion is probably a result of the presence of warm (but salty) southern water

Table 1

Meteorological Statistics
(36-42.13N - 122-1.76W)

Remarks	Time	SST (°F)	Wind/Dir (Knots/deg)	Air Temp (°F)		DD	Pyrometer kJm^{-2}
	0735		9/N				
	0805		6/NE			0	
	0900		8/NNE	57°		49.5	
	0910	55°F	9/NNW				
	0920		11/NW			57.2	
	0930	55°	11/NW	56°	55	66.7	
3' chop	0943		11/NW			70.5	
white caps	1010	55°	11/NW			74.3	
3' chop	1116		10/NW	57°	56	78.2	
	1147	55°	12/NW			87.7	
	1247	55°	11/NW			85.8	
	1303		9/NW			85.8	
	1350		14/NW			108.7	
very choppy	1410	55°	14/NW	59°	57	112.5	
	1430		16/NW			104.8	

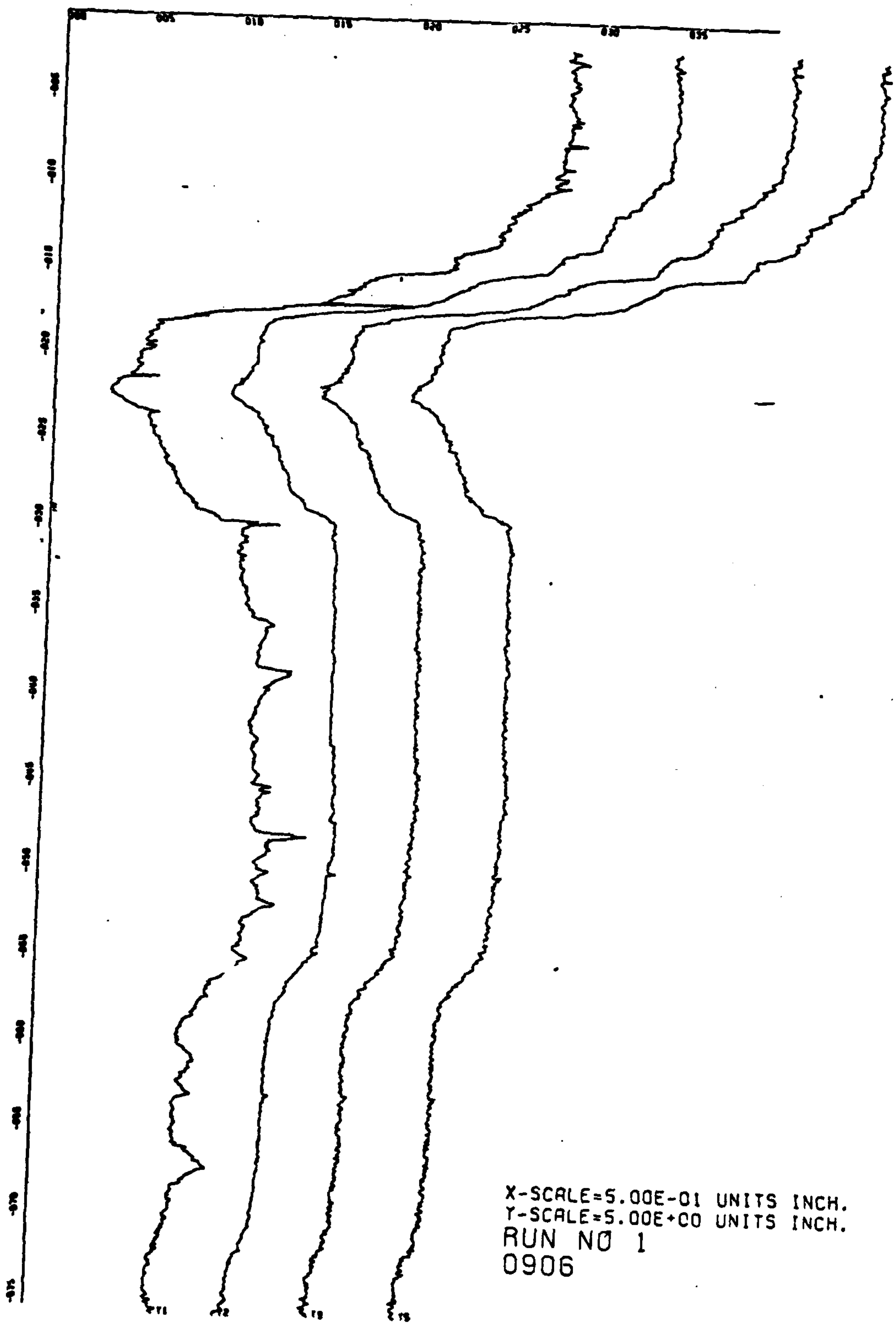


Figure 3. Microstructure Profile, 0906

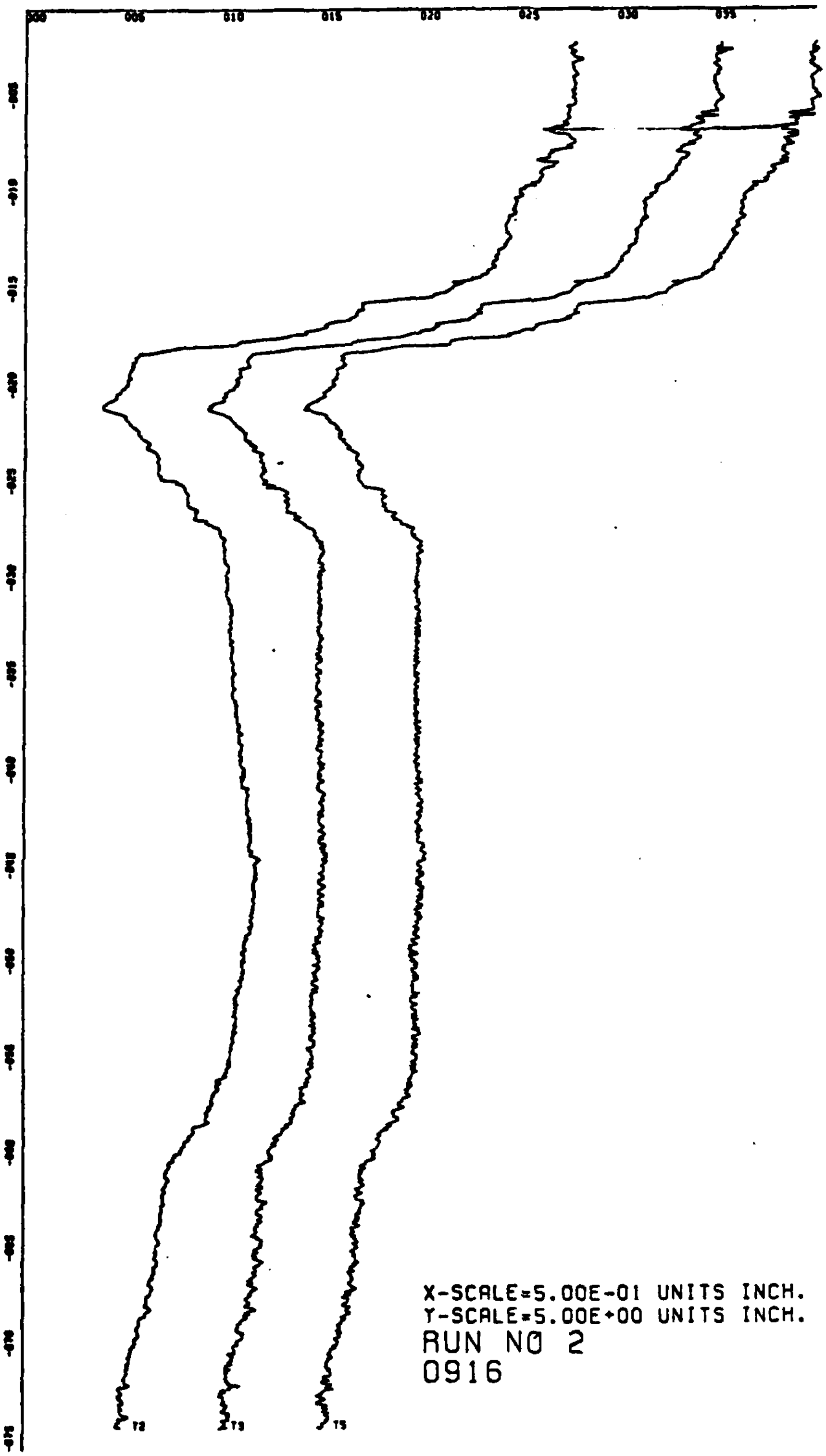
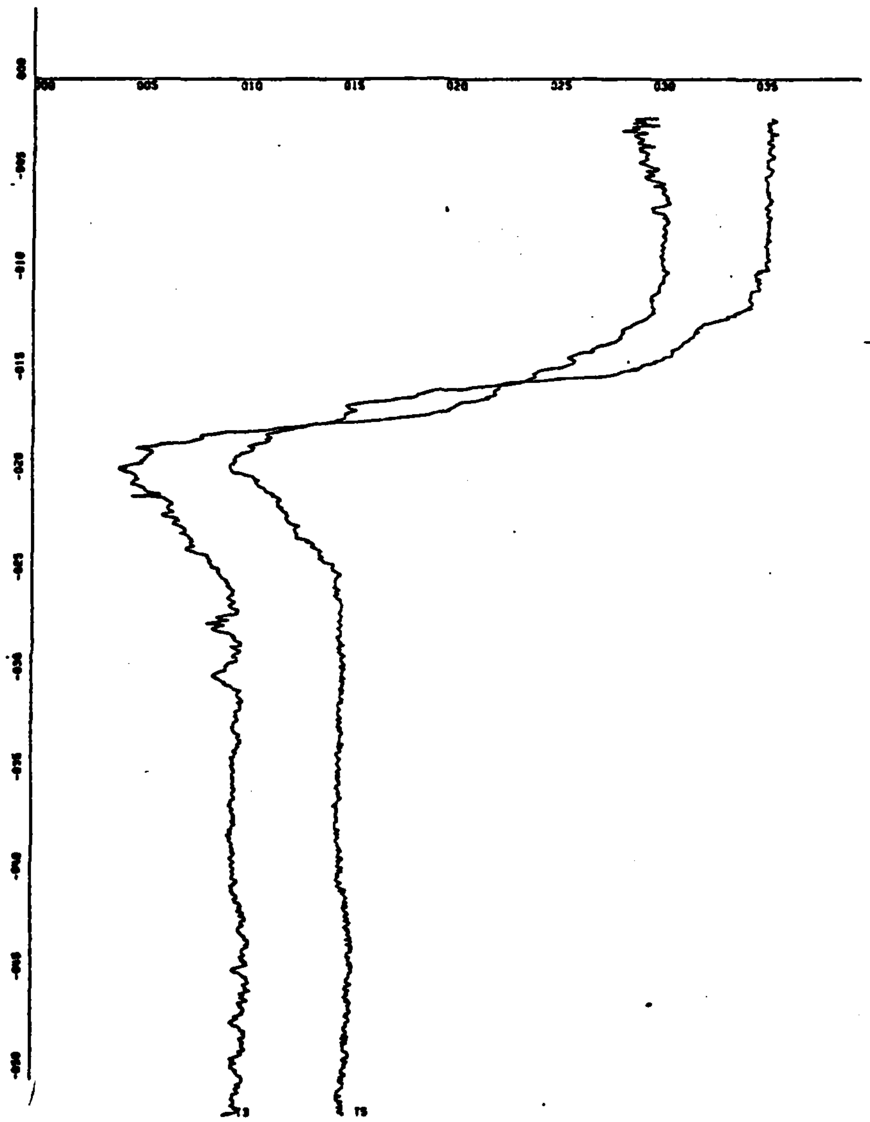


Figure 4. Microstructure Profile, 0916



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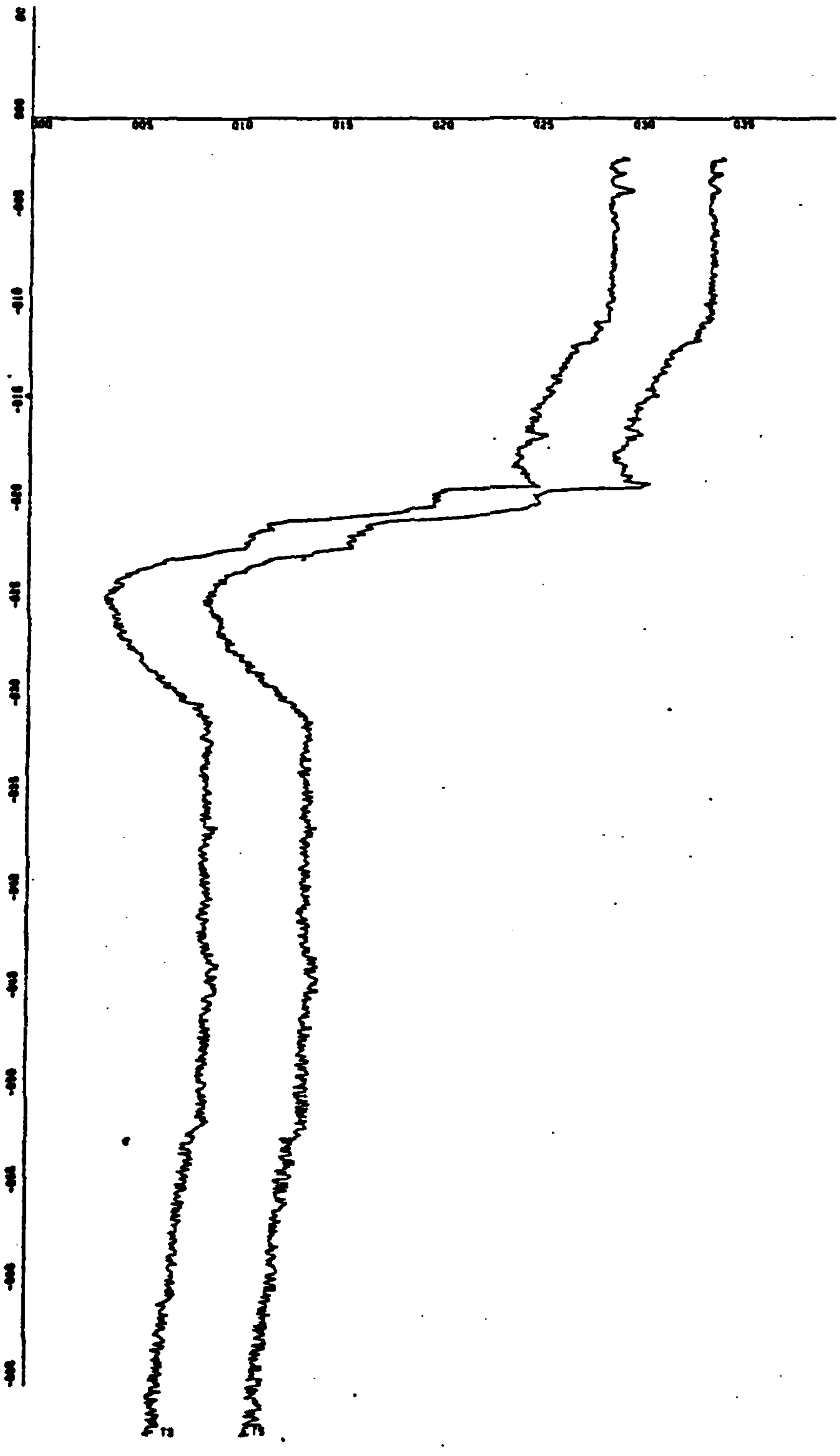
Y-SCALE=5.00E+00 UNITS INCH.
RUN NO 3
0927

Figure 5. Microstructure Profile, 0927



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Y-SCALE=5.00E+00 UNITS INCH.
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1009

Figure 6. Microstructure Profile, 1009

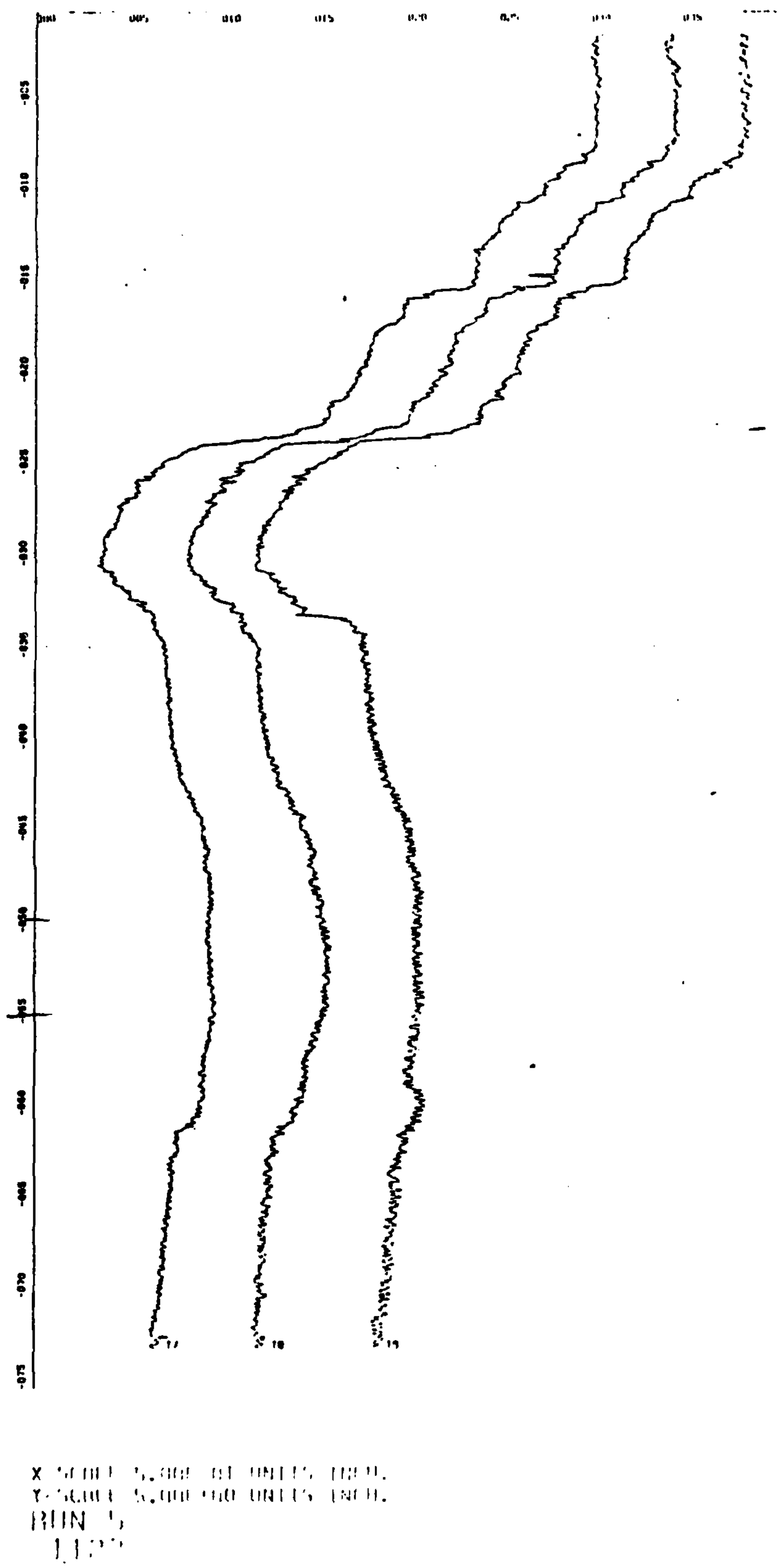
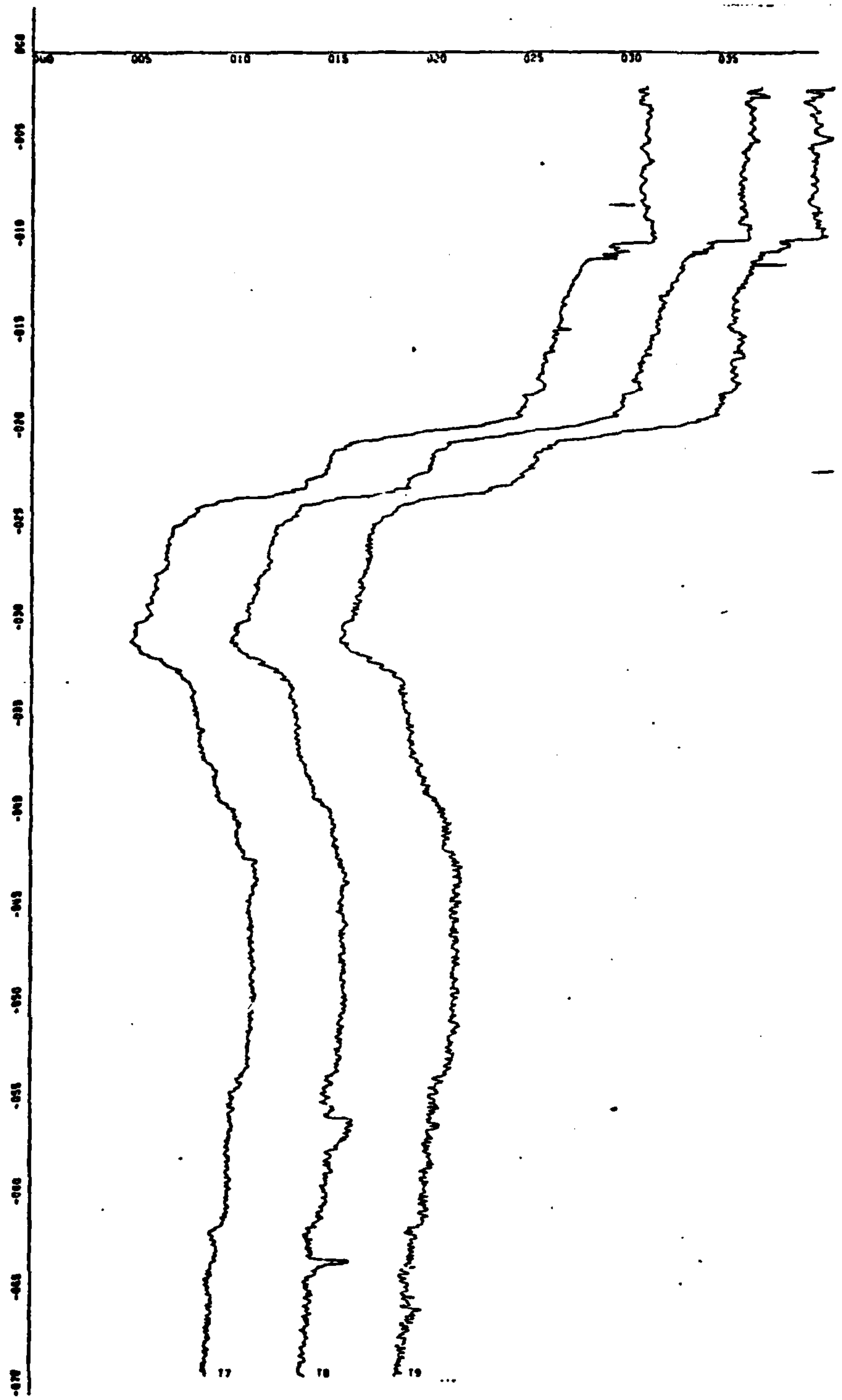


Figure 7. Microstructure Profile, 1122



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Y-SCALE=5.00E+00 UNITS INCH.
RUN OG
1144

Figure 8. Microstructure Profile, 1144

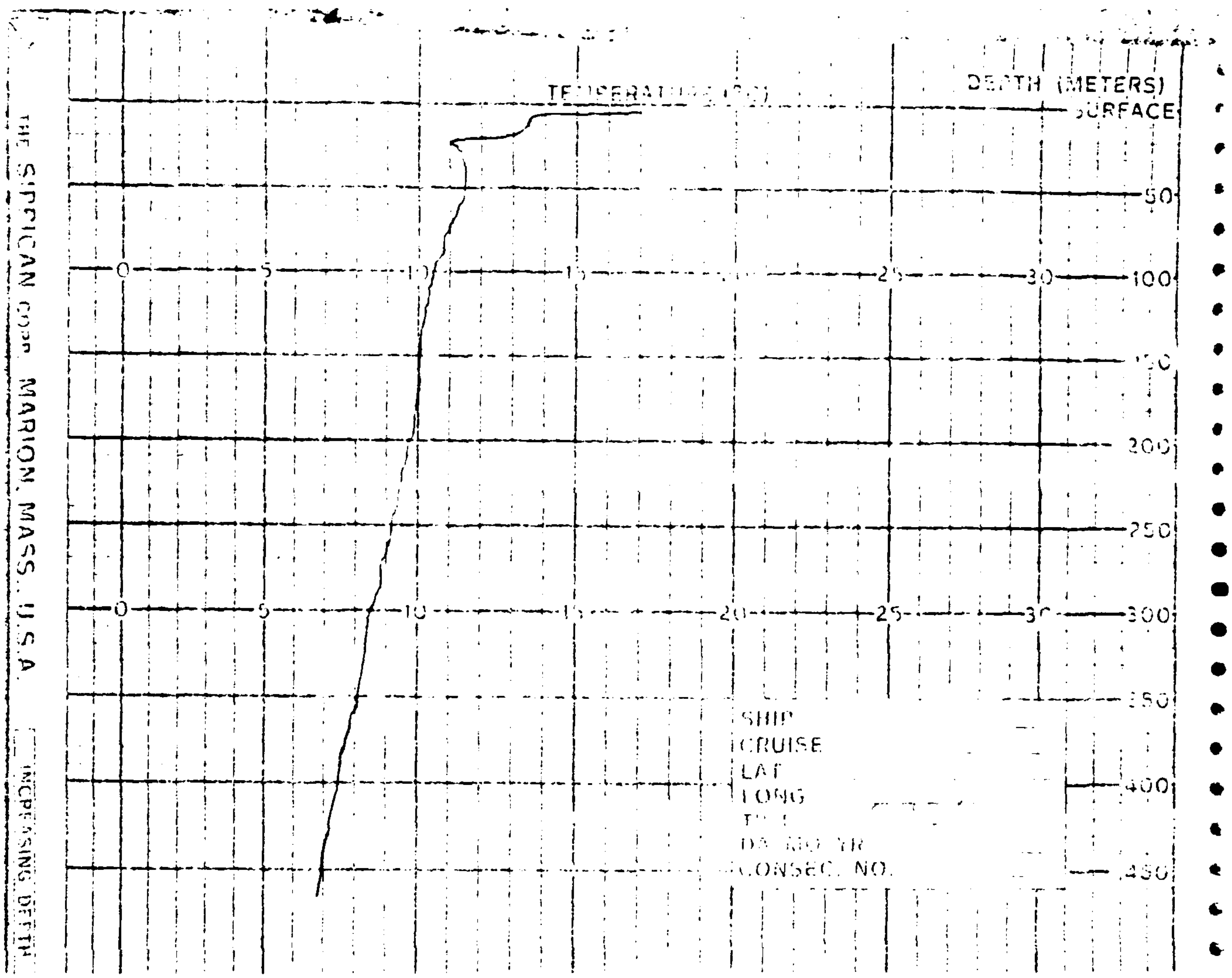

Figure 9. XBT Trace, 0920

advancing north from Baja, California. This inversion is very fortuitous in that the obvious large scale interleavings of the two water masses are a good example of the onset of a layered structure, the refinements of which will eventually contribute to a pervasive fine scale and microscale structure. The presence of the gross features is an indication that large scale mixing is occurring and that broad turbulence exists. The correlative to the presence of large scale turbulence is the lack of refinements or relative paucity of the final stages of microstructure development are the result of incomplete mixing. The classic layers and sheets or step-like features that indicate microstructure are consequently absent except for occasional examples. A display of these sheets and layers can be noted at -26 meters, -51 meters and -63 meters (profile number 1). Some particularly good examples can be seen in the thermocline on profile number 4 (circled), and between -25 and -28 meters on profile number 2. A further magnified portion of the circled features on profile 4 (Figure 10) shows a closeup of the thermocline with some examples of layers and sheets. An excellent example of the step-like structure can also be seen on the larger scale on the XBT trace at depths well below the temperature minimum.

It is important at this point to determine whether the data being analysed is real or instrument induced, i.e., the result of microstructure or system noise. Two observations indicate that the data of the selected thermistors is indeed

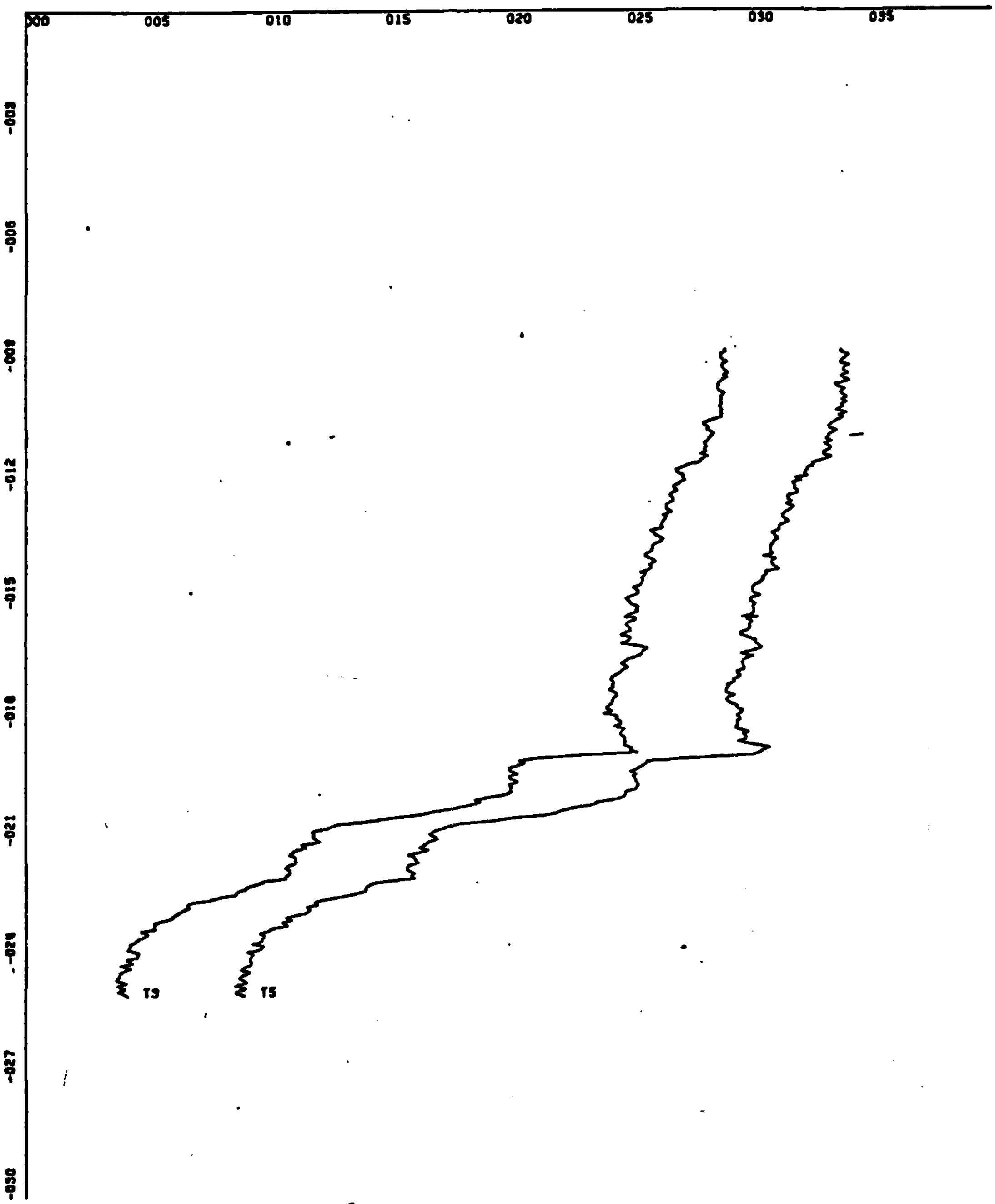

Figure 10. Magnified Microstructure, 1009

real. The first indicator is that most microscale features are reflected on all reliable thermistors providing a correlation which noise would not have. Additionally, it can be seen that thermistor T2, although relatively unresponsive, does act as a low pass filter and consequently prominent microscale features can be easily identified, and then seen in thermistors T3 and T5. This evidence alone is convincing that the data is real.

A Fourier analysis was performed on each reliable thermistor profile. The ensemble of Fourier analyzed profiles were then summed to form a spectral density. A spectrum was calculated for both the gradients and the perturbations from the mean. The perturbations were produced by subtracting a ten point running mean from the profile which yielded only the deviations about the mean. Examples of the gradient and perturbation profiles for Run No. 1 are shown in Figures 11 and 12 respectively. Using perturbations and gradients had the advantage of removing the dominating influence of the thermocline. Figure 13 shows a log-log plot of the gradient spectrum. It shows that the major contributor to the spectrum is centered at 1/2 cycle per meter or a 2 meter wavelength. The fall off in the lower frequencies is most likely a result of the filtering produced by a differentiated signal. Thus the peak may be more artificial than real. In the higher frequencies, which are less filtered, it is encouraging to note that the spectrum tends to approximate a -5/3 slope indicating small scale isotropic turbulence and not noise. A similar

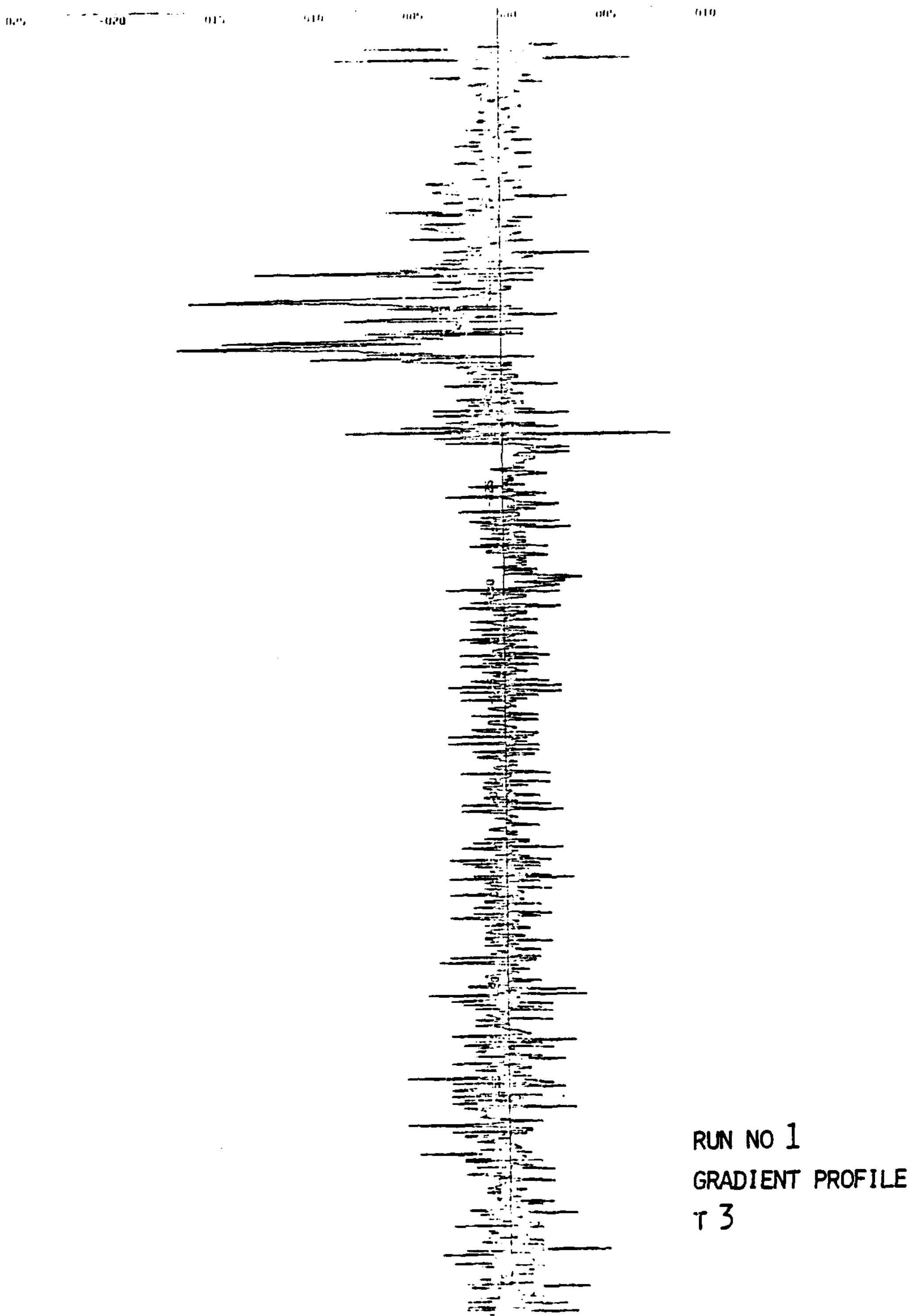

Figure 11. Gradient Profile, Run No. 1

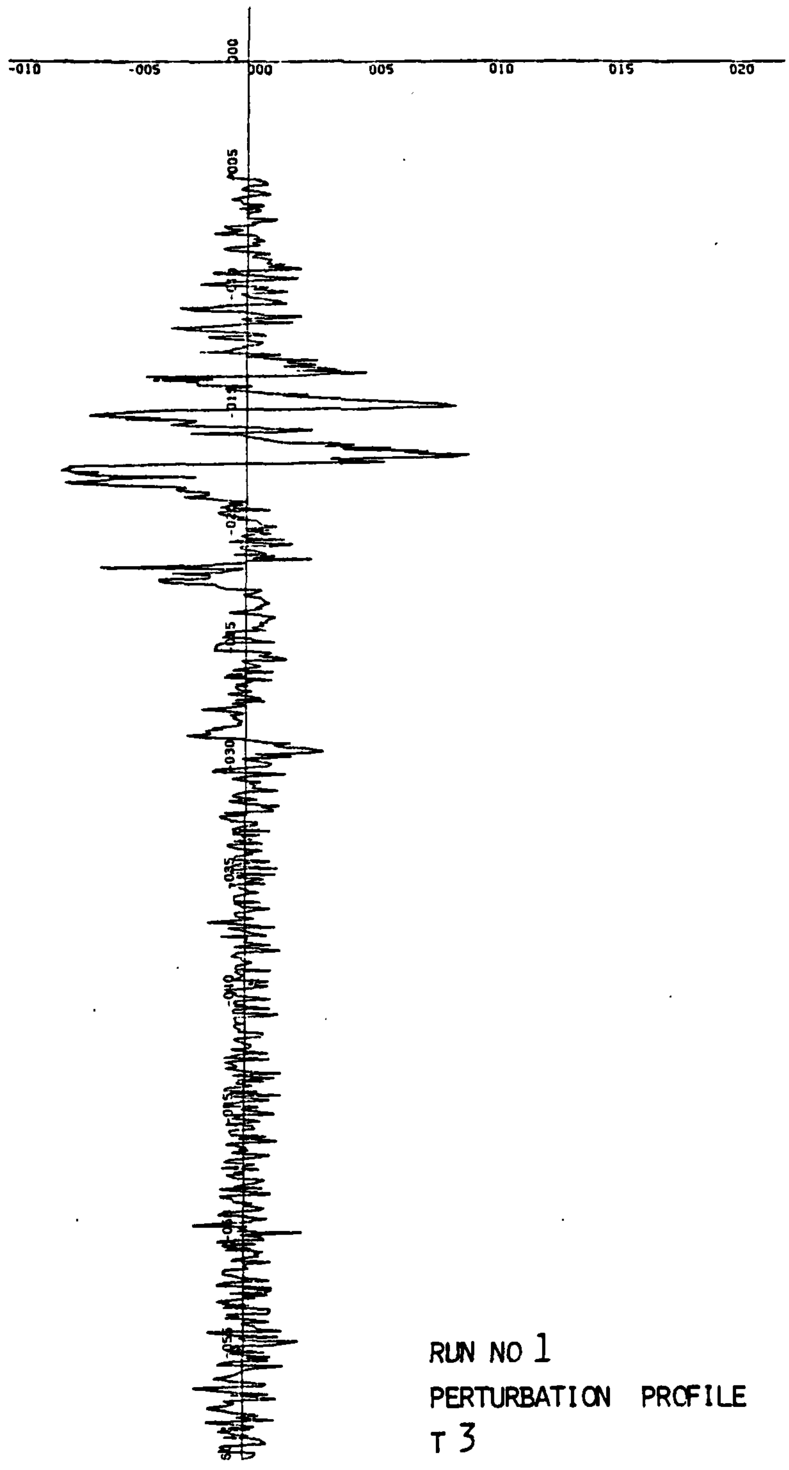

Figure 12. Perturbation Profile, Run No. 1

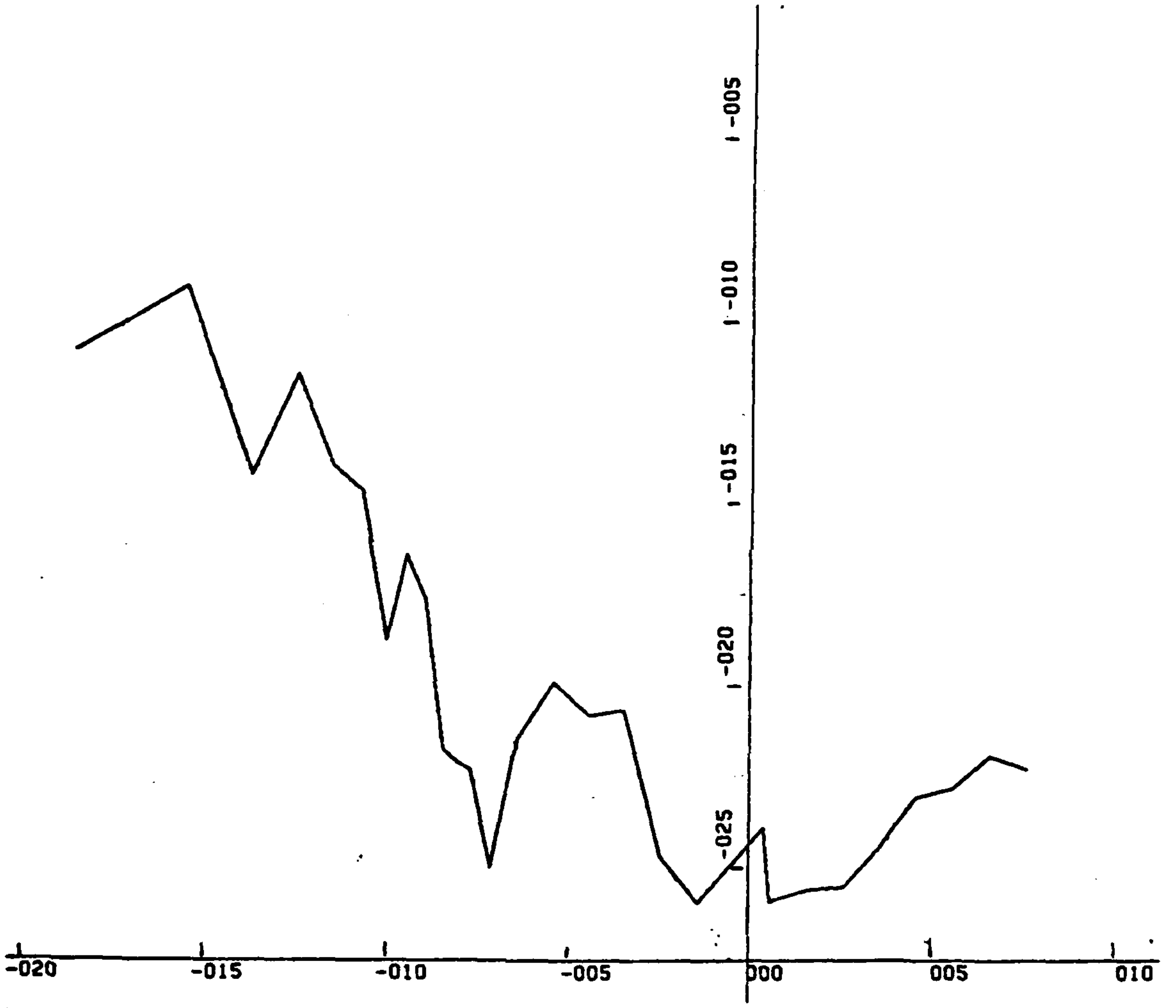

Figure 13. Gradient Spectrum of Microstructure

spectral analysis was performed on the perturbations as shown in Figure 14. As can be seen, the high frequency spectrum of the perturbations and gradients are similar except that at about 0 (1 cycle/meter) on the perturbation spectrum, the energy density increases indicating non-isotropic turbulence which is consistent with past investigations such as Reference 14. It would seem reasonable to consider as another definition of microstructure as as being that point at which there is an increase in the spectral density at higher frequencies.

As stated in the section on theory, a possible indicator of the relative amounts of large scale and small scale turbulence is given by the Cox numbers. Each profile was broken up into 3 meter segments and Cox numbers were established for each segment. The $(\overline{\partial T}/\partial z)$ in the denominator of equation 1 refers in this case to the average gradient in the 3 meter segment and not to the average gradient for the entire profile. Table 2 gives a listing of the Cox numbers by depth which are also graphed in Figure 15. Large Cox numbers indicate broad scale turbulence while small Cox numbers indicate small scale turbulence or layering. The correlation between the numbers and the visual profiles is very high. The most homogeneous layers have Cox numbers many orders of magnitude greater than the most layered sections. The two most obvious features from Table 2 are the presence of a very stratified region (low Cox numbers) centered at about 15-18 meters in profile 1 and remaining at that same level through profiles 2 and 3. The first 3 profiles were run within 20 minutes of each other. In subsequent

Figure 14. Perturbation Spectrum

Table 2. Cox Numbers

Depth Interval (m)	THERMISTOR 1	2	3	4	5	6
0 - 3	74,188	43,854	34,371	12,686	35,381	15,701
3 - 6	54,545	32,504	20,227	36,946	31,904	79,082
6 - 9	531	1,225	21,454	100,858	506	189,237
9 - 12	624	538	1,909	475	145	580
12 - 15	161	120	94	323	348	930
15 - 18	92	105	85	4,644	215	494
18 - 21	49,165	377	677	116	201	162
21 - 24	86,946	488	306	124	173	97
24 - 27	22,856	366	130,062	486	219	240
27 - 30	130	1,444	430,860	408	418	379
30 - 33	837,613	340,316	17,504	29,003	226	499
33 - 36	485,441	102,196	26,937	51,747	1,341	672
36 - 39	688,324	27,523	80,131	457,753	7,391	672
39 - 42	406,223	1,431,438	14,323	488,548	4,787	621
42 - 45	10,418	2,857,446	32,554	6,230	1,988	27,306
45 - 48	6,807	57,739	164,688	14,130	7,313	311,738
48 - 51	7,508	66,047	23,825	33,642	17,941	135,411
51 - 54	4,644	592,073		7,683	9,238	22,394
54 - 57	549	255,820		5,640	29,801	6,352
57 - 60	3,876	1,013		734,694	4,480	7,642
60 - 63	32,002	4,349		75,552	2,717	304,129
63 - 66	18,411	10,705		499,295	5,815	1,725,045
66 - 69	7,410	2,624			11,372	4,857,190
69 - 72	1,946	2,613			59,050	
72 - 75	1,131					
75 - 78					(12,366)	(477,914)
78 - 81						

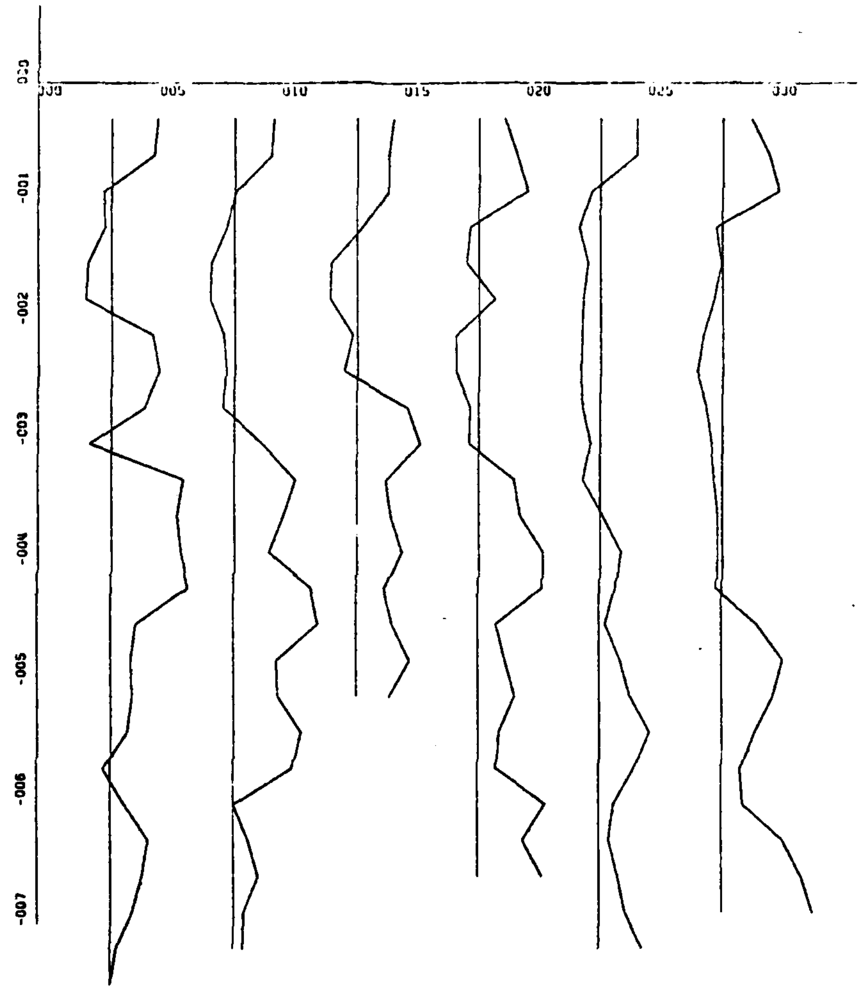

Figure 15. Sequential Cox Numbers Plotted in Log-Log Scale

profiles, this layer deepens slightly but thickens greatly. Therefore it is natural to presume that the surface forcing functions are maintaining the mixed layer and thermocline in a reasonably steady state. The regions below the temperature minimum are much more dynamic however and changes in the profile are being reflected hourly.

As anticipated, the originally sharp temperature minimum is broadening, however it is doing so on the microscale. That is, as the gradient below the thermocline weakens, microstructure is being created over a large segment of the profile. In profile 6, the last analyzed profile, small Cox numbers exist from 9 meters to 42 meters, at which point broad scale turbulence is again set up.

The Cox numbers indicate that the mixed layer has not deepened appreciably and that a diurnal thermocline has not begun to form. All of the major changes in the profile appear to be taking place in and below the site of the main thermocline. The homogeneous (turbulent) layer that is so prominent from -30 to -42 meters is being displaced downward to some degree, but principally it is being broken up, that is, layered. The thermocline and top of the inversion are being broadened as they become less abrupt.

As described in Section III, double diffusion processes will modify the existing strata which will be either stabilized or destabilized depending upon the character of the layering. A result of the interposition of warm salty southern water from about -30 to -55 meters is a large scale temperature inversion which remains very evident throughout the entire data collection period of 6 hours. It is a reasonable assumption then, that because of the longevity of the feature, the temperature inversion is stable. The top of the inversion represents a lamination of cooler, fresher water over warm salty water.

The bottom of the inversion on the other hand is structured with the more common warm salty water over cooler fresher water. Fine scale or larger turnover of the water is presumed being caused by the Kelvin-Helmholtz phenomena, which is especially effective in the strong gradients at the top of the inversion. The double diffusion processes (cooler fresher water over warm salty water) then effect the microscale by creating more stable conditions at the top of the inversion. This broadening of a stable region is evident from the Cox numbers, Table 2. Toward the bottom of the inversion a destabilizing process, as a result of double diffusion activity (warm salty water over cooler fresher water), should be indicated by the formation of larger Cox numbers. This too can be seen from Table 2.

Although the Cox numbers appear to adequately describe the physical phenomena, it seems necessary to question their complete applicability. The Cox number is very dominated by the denominator which in the case of an isothermal column would tend to cause the ratio to approach infinity. The equation therefore directly ties microstructure to the mean gradient, which is admittedly an indicator of the scale of turbulent activity. The deviations about the mean also make contributions, but in a near isothermal layer, these contributions would be insignificant in effecting the relative size of the Cox number. Furthermore, in theory, the numerator (local gradient) could conceivably go to infinity at a discontinuity. With digital data however, infinite gradients are not calculated because the gradient is calculated across a finite depth. Therefore it is concluded that the Cox number is not sensitive to microstructure in areas of strong, variable mean gradients as in the upper layers of the ocean.

VI. CONCLUSIONS

(1) The Cox numbers as used with these data probably have little application beyond indicating the relative magnitude of the mean gradient. This is principally because in the upper layers, the mean so overwhelmingly dominates the perturbations, that any subtleties in the latter would be masked. Application of the Cox number in deeper regions of the ocean is a more useful indicator of microstructure activity.

(2) It is apparent that because of the lack of insolation, the basic experiment did not provide the data needed to observe changing microstructure relative to surface forcing functions. The data was fortunate however in that it provided a large scale feature that was observed to modify from internal forcing functions rather than surface forcing functions. In this case, the two processes at work are most likely to be internal wave activity and double diffusion.

(3) This experiment could have been much more informative if the equipment were able to resolve temperature differences less than a 6.6 cm interval. This sampling rate was selected as a result of fall rate, number of thermisters and storage capacity of the Hewlett-Packard 9831A computer. The 6.6 cm sampling rate effectively limited the experiment to data that is somewhat between microscale and fine scale. As a result, the microstructure only begins to be evident in the gradient and perturbation spectra.

(4) The anomalous gross thermal structure was of great interest and allowed investigation of the early stages of water mass interleavings. The erosion of the inversion and tendency to be assimilated into the mean profile is evident hour by hour. It is interesting to note that the profile was made up of two distinct areas, one of high gradient and one of low gradient. In the high gradient areas, the Väisälä frequency is too high for continuity of microscale features from one profile to the next while in the isotropic regions, the broad turbulent activity is transitory on the microscale. The ideal situation for observing microscale phenomena would be a moderate gradient over a longer depth interval. As indicated on the XBT trace, a deeper profile would have provided this.

(5) The profiler constructed and used specifically for this experiment functioned as designed. Future temperature microscale investigations should however include some equipment additions and modifications. Foremost, it is imperative to have some salinity measurements as provided by an S-T-D probe. This would have shed light on the characteristics of the temperature inversion that could have been used in better describing the microscale activity. Another major step forward will be taken with the introduction of a data telemetry system. A free falling, untethered probe is vastly superior to one that is loosely tethered, especially under adverse surface conditions.

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